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SIMULATION OF LOW LEVEL EXPLOSIVES BLAST LOADINGS AT FULL SCALE--ETC(U)
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MEMORANDUM REPORT ARBRL-MR-02853

SIMULATION OF LOW LEVEL EXPLOSIVES BLAST LOADINGS AT FULL SCALE BY MODIFICATIONS TO BRL DUAL SHOCK TUBE FACILITY

Edmund J. Gion

July 1978

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) MEMORANDUM REPORT ARBRL-MR-02855	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) SIMULATION OF LOW LEVEL EXPLOSIVES BLAST LOADINGS AT FULL SCALE BY MODIFICATIONS TO BRL DUAL SHOCK TUBE FACILITY.		5. TYPE OF REPORT & PERIOD COVERED Final rept,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Edmund J. Gion		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Ballistic Research Laboratory ATTN: DRDAR-BLL Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Armament Research & Development Command U.S. Army Ballistic Research Laboratory ATTN: DRDAR-BL Aberdeen Proving Ground, MD 21005		12. REPORT DATE (11) JULY 1978
		13. NUMBER OF PAGES 42
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 41p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

(18) SBIE (19) AD-E430 104

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shock Tubes
Blast Waves
Simulated Blast Waves
Blast from Explosives

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A concept is described permitting "full scale" (ner) testing of walls, of 3.7m (12 ft) height under simulated explosive blast loadings with pressures about 70 kPa (10 psi), 50ms positive duration.

The existing BRL 2.4m (8 ft) diameter shock tube with modification was the hardware motivating the inquiry; and this hardware is used by way of example in the calculation of numbers and graphs. An enlarged 3.7m test or → next page

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cont. driven section is added to the 2.4m driver section to accommodate full scale test dimensions. The normal straight shock tube operating cycle is then extended by testing at a location where the reflected expansion waves from the breech overtake and weaken the shock. The resulting pressure loading is a decaying pulse (i.e., blast-wave type) with determinable duration.

A requirement on the loading duration may conversely be used to specify the appropriate tube lengths involved. The methods are described which account for the differences in operation between a straight and an area-changed shock tube, which apparently have not been done before for the sub-sonic conditions encountered here.

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I. INTRODUCTION

Recently, the Army has shown interest in minimizing "collateral damage" to civilian areas and to friendly troops. This interest has created a need for facilities to permit "full scale" testing under simulated low-level blast loadings caused by explosive charges. ("Full scale" walls would be of realistic sizes wherein regular construction materials and methods are useable.) The need for such facilities apparently has not been met satisfactorily. Facilities exist, e.g. the DASACON conical tube at Dahlgren, Virginia, permitting full scale testing; yet operationally they may have shortcomings: expense of operation in terms of manpower and/or energy requirements or, inadequate simulation of the waveform characteristics of conventional explosive blast waves. In response to an Army request involving such full scale testing, we have studied a possible modification of the 2.4m (8') tube portion of the existing BRL Dual Shock Tube Facility[1,2], Figure 1 from Reference 1, to give the desired testing parameters - acceptance of walls to 3.7m (12') height, subjected to peaked pressure pulses up to 70 kPa (10 psi) of $\sim$ 50ms positive duration.

Testing beyond the open end was not considered because of the jet-like characteristics of the flow emitted. Close in, pressures are uneven across a planar surface immersed normal to the flow, a result predicted from a simple model, and found in early experiments by Bertrand[2]. Farther away, when the shock is more planar, the desired pressure levels are not assured under the tube's operating limits.

The modification considered is basically an adjustment on the driver/driven tube lengths and test station location to give the desired pressure wave form, and is a somewhat natural extension of the classical shock tube operation cycle, but with an area change. The peaked pressure waveform is obtained by testing at stations within a distance interval defined by the intersection of the leading and trailing waves of the breech-reflected expansion fan with the primary shock. The interaction of the expansion waves with the shock weakens it, thereby giving the desired decaying pressure pulse. The flow in an equivalent straight shock tube is used to follow the wave processes. Specifying the desired positive duration of the peaked wave then determines the appropriate tube lengths, for the straight tube; then, by imposing a simple physical requirement, these tube lengths can be carried over to determine the desired area-changed tube lengths.

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1. *B. P. Bertrand, "BRL Dual Shock Tube Facility," BRL MR 2001, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1969. AD 693264.*

2. *B. P. Bertrand, "Proposed Improvement of BRL Dual Shock Tube Facility," BRL Technical Note No. 1733, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1970. AD 871736.*

The driving pressures for the area-changed shock tube are computed following the methods of Alpher and White,[3] who also treated area-changed shock tubes but whose interests were in stronger shocks, with the driver tube looking into a smaller area driven tube. The principal features of our calculations apparently have not previously been done explicitly for the subsonic flows occurring here and up to the wave interaction regions involved. Results are presented of calculations for the driver pressures for the 2.4m tube for several test conditions, involving two different (larger) areas of driven tube.

II. DETERMINATION OF DRIVER PRESSURE

The flow situation for the area-changed tube is depicted in Figure 2, along with its wave diagram or x-t plot. Following Alpher and White, we may write the expression for the diaphragm pressure ratio p_{4c}/p_1, after the diaphragm is broken and flow processes are established, as (ideal, one-dimensional flow throughout)

$$\frac{p_{4c}}{p_1} = \frac{p_{4c}}{p_{3a}} \frac{p_{3a}}{p_3} \frac{p_3}{p_2} \frac{p_2}{p_1} \qquad (1)$$

The pressure ratios in the expression are interpreted to be

p_{4c}/p_{3a} - the pressure (ratio) required to expand unsteadily the gas in region 4 from rest to a Mach number M_{3a};

p_{3a}/p_3 - the pressure required to expand steadily the gas from M_{3a} to M_3*;

p_3/p_2 - the pressure across the contact surface separating driver- from driven-gas, with $p_3 = p_2$;

p_2/p_1 - the pressure required to compress the test gas in region 1 through the shock of strength M_1 or M_s.

Assuming the processes are isentropic and accounting for the steady or unsteady nature, we may write Equation (1) as

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3. *R. A. Alpher and D. R. White, "Flow in Shock Tubes with Area Change at the Diaphragm Section," J. Fluid Mech 3, 457-70 (1958).*

**For subsonic flow M < 1, a steady expansion is more efficient in the conversion of thermal to kinetic energy than an unsteady expansion.*[4]

4. *E. L. Resler, Shao-Chi Lin, and Arthur Kantrowitz, "The Production of High Temperature Gases in Shock Tubes," J. Appl. Phys. 23, 1390-99 (1952).*

LIST OF TABLES

$$\frac{p_{4c}}{p_1} = \left\{ (1 + \frac{\gamma_4 - 1}{2} \; M_{3a}) \; \left[\frac{2 + (\gamma_4 - 1)\; M_3^{\;2}}{2 + (\gamma_4 - 1)\; M_{3a}^{\;2}}\right]^{\frac{1}{2}} \right\}^{\frac{2\gamma_4}{\gamma_4 - 1}} \quad \frac{p_2}{p_1} \tag{2}$$

In regular shock tube testing, the gases in regions 1 and 4 are usually specified, as is the desired test overpressure; thus a driver pressure can be determined. In the area-changed tube the unknowns are p_{4c} as well as M_3 and M_{3a}. Equations to connect these are the expression for isentropic nozzle flow in terms of the nozzle areas:

$$\frac{A_4}{A_1} = \frac{M_3}{M_{3a}} \; \left[\frac{2+(\gamma_4-1)\; M_{3a}^{\;2}}{2+(\gamma_4-1)\; M_3^{\;2}} \right]^{\frac{1}{2}\frac{\gamma_4+1}{\gamma_4-1}} \tag{3}$$

and an expression connecting M_3 with the driven gas:

$$M_3 \equiv \frac{u_3}{a_3} = \frac{u_3/a_1}{a_3/a_1} = \frac{u_2/a_1}{(a_3/a_{3a})\;(a_{3a}/a_4)\;(a_4/a_1)} \tag{4}$$

where a similar decomposition into steady-unsteady processes as in Equation (1) is made, and results in:

$$M_3 = \frac{(u_2/a_1)(a_1/a_4)}{\left[\frac{2+(\gamma_4-1)\; M_{3a}^{\;2}}{2+(\gamma_4-1)\; M_3^{\;2}}\right]^{\frac{1}{2}} \; \frac{2}{2+(\gamma_4-1)\; M_{3a}}} \tag{5}$$

We now combine Equation (5) with Equation (2) and rewrite (2) as

$$\frac{p_{4c}}{p_1} = \left[\frac{(u_2/a_1)\;(a_1/a_4)}{M_3}\right]^{-\frac{2\,\gamma_4}{\gamma_4-1}} \quad p_2/p_1 \tag{6}$$

Equations (5), (6) and (3) may then be used to determine the required driver pressure p_{4c}, knowing the desired testing pressure p_2/p_1 and the nozzle area ratio A_4/A_1. Solution techniques - e.g. the Newton-Raphson method or iteration - may be used on this system of equations.

We have used a graphical procedure offering some simplicity and utility to the worker at the site. This is now illustrated. From Equation (3) we have

$$\left(\frac{A_4}{A_1}\,\frac{M_{3a}}{M_3}\right)^{\frac{\gamma_4-1}{\gamma_4+1}} = \left[\frac{2+(\gamma_4-1)\,M_{3a}^2}{2+(\gamma_4-1)\,M_3^2}\right]^{1/2} ,$$

which, on substituting into Equation (5), gives

$$M_3 = \frac{(u_2/a_1)\;(a_1/a_4)}{\left(\frac{A_4}{A_1}\;\frac{M_{3a}}{M_3}\right)^{\frac{\gamma_4-1}{\gamma_4+1}}\;\frac{2}{2+(\gamma_4-1)\,M_{3a}}} \tag{7}$$

Or rearranging

$$2\,\frac{(A_4/A_1)^{\frac{\gamma_4-1}{\gamma_4+1}}}{(u_2/a_1)\;(a_1/a_4)}\,M_3^{\frac{2}{\gamma_4+1}} = \frac{2+(\gamma_4-1)\,M_{3a}}{M_{3a}^{\frac{\gamma_4-1}{\gamma_4+1}}} \tag{8}$$

The right hand side of Equation (8) determines a curve Z_{3a} plotted vs Mach number; similarly, the left hand side determines a curve Z_3 (a straight line on a log-log plot). Thus for given p_2/p_1 - or $(u_2/a_1)\;(a_1/a_4)$ - and A_4/A_1, the points $Z_3 = Z_{3a}$ determine the Mach numbers M_{3a} and M_3 upstream and downstream, respectively, of the nozzle, and in particular M_3 of Equation (6) and, thereby, the required driver pressure p_{4c}.

Some sample values have been calculated for their specific interest and to illustrate the procedure. An attractive feature is that different area ratios and test pressures are reflected only in a change in (straight line) intercept (for the same gases) of the Z_3 curve. The area ratios considered were for 2.4m (8') diameter driver tube and Case (a)-3.7m (12') and Case (b) - 4.6m (15')

diameter driven tubes, with a test overpressure p_{2g} = 73 kPa (10.6 psi). Gases had

$$\gamma_4 = \gamma_1 = 7/5; \; a_4 = a_1 \quad .$$

Case (c) is similar to (a) but p_{2g} = 34.5 kPa (5.0 psi). The values for the various quantities entering into the construction of the graph are tabulated in Table IA.

TABLE IA - PARAMETERS FOR TEST FLOWS

Case	(A_4/A_1)	u_2/a_1	M_1	$2(A_4/A_1)^{1/6}(u_2/a_1)$	p_2/p_1
a	0.444	0.4022	1.27	4.346	1.72
b	0.284	0.4022	1.27	4.033	1.72
c	0.444	0.219	1.14	7.982	1.34

The graphs for these cases are plotted in Figure 3 as functions of Mach number.

For the three cases the Mach numbers determined are tabulated in Table IB as well as the driver pressures (absolute) as determined from Equation (6).

TABLE IB - CALCULATED NOZZLE MACH NUMBERS AND DRIVER PRESSURES

Case	p_{4c} (kPa)	p_{4c} (psi)	$\sim M_{3a}$	$\sim M_3$
a	800	116	0.6	0.50
b	1564	227	0.68	0.55
c	252	37	0.40	0.25

From these sample cases, it is seen that a 2.4m diameter driver section coupled to a 3.7m diameter driven section to give test overpressures up to 70 kPa (10 psi) is well within the 1100 kPa operating limits of the present TBD 2.4m shock tube. A 4.6m driven section at this overpressure could not be accommodated, however. For reference we have considered a range of test over-pressures p_{2g} and their required driver pressures p_{4c} for the 2.4m: 3.7m (8':12')

area-changed tube. Results are plotted as Figure 4.* Maximum p_{2g} is seen to be ∿ 93 kPa (13.5 psi) for the 1100 kPa driver operating limit.

In addition, some cases have also been treated involving the 1.7m (5 1/2') diameter tube of the BRL Dual Shock Tube Facility, to illustrate the obtainable test pressures, along with associated driver pressures. Wave durations were not worked out. The 1.7m tube has provision for heating of the driver gas to eliminate the contact surface discontinuity, i.e. for tailoring of the interface.

For small disturbances, identity of the acoustic impedance ρa across the interface assures that waves are transmitted without change. For the same gas on either side of the interface, the requirement reduces to identity of the sound speeds. Hence, also, in the tailored-interface mode

$$u_2/a_2 = u_3/a_3 = M_3.$$

With the desired test condition (hence M_3) known, one may enter the plot of Figure 3 to select a particular pair (there is a range) M_3 , M_{3a} for which $Z_3 = Z_{3a}$, as required by Equation (8) in the solution for p_{4c}. Through this point (M_3,Z_3) is passed a straight line paralleling previously computed straight-line Z_3 curves for other conditions; and this gives the intercept value, from which the driver sound speed ratio a_4/a_1 is determinable. Consequently, the driver gas temperature or the heating may be determined. Then the driver pressure including the heating is again determined from Equation (6). Three sample cases are given in the following Table II, for the 1.7m tube coupled to a 3.7m diameter driven tube, with $T_1 = 300^\circ$ K.

**Because of the relatively large exponent occurring in Equation (6), small rounding errors in the early stages of calculations can yield variations from our final results. The accuracy conforms to the approximate nature of the inquiry, and does not appear to be the limiting feature in the tube modification.*

TABLE II. CALCULATED (ABSOLUTE) DRIVER PRESSURES FOR 1.7m (5½') DIAMETER TUBE OPERATING IN TAILORED-INTERFACE MODE

Case	p_{2g} (kPa)	p_{2g} (psi)	M_1	p_2/p_1	a_2/a_1	u_2/a_1	M_3	$\sim M_{3a}$	Intercept value	a_4/a_1	T_4 °K	p_{4c}/p_1	p_{4c} (kPa)	p_{4c} (psi)
1	73.0	10.6	1.27	1.72	1.083	0.4022	0.3714	0.43	5.62	1.466	645	13.95	1413	205
2	34.5	5.0	1.136	1.34	1.043	0.213	0.2043	0.25	9.55	1.319	522	6.96	703	102
3	51.7	7.5	1.199	1.510	1.062	0.3041	0.2864	0.39	7.1	1.400	588	10.47	1061	154

III. DETERMINATION OF POSITIVE PULSE DURATION

A. Wave Advance in the Straight Shock Tube

We turn now to questions on the positive duration of the desired peaked wave. As mentioned in the Introduction, we rely on the interaction between the incident shock $S_{\rightarrow}$ and the reflected rarefaction wave $R_{\leftarrow}$ from the breech to weaken the shock pressure, thus giving the peaked pressure wave form. The wave diagram of Figure 5, for a straight shock tube, illustrates a possible set of events and the pressures at various stations x. For sufficiently strong rarefaction waves the shock reduces to one of the characteristics of the rarefaction wave exiting from the interaction region; for weak rarefaction waves overtaking the shock, a weakened shock with lowered shock pressures emerges[5]. In both instances we may take the peaked wave's positive duration as the interaction time of the shock with the reflected expansion fan from the driver breech. The problem, therefore, is to determine this time from the operation cycle of our area-changed shock tube.

As a point of departure, we make use of calculations involving a straight shock tube chosen to give the same downstream conditions as the area-changed tube. The interaction problem and the relevant times will be solved for the straight tube. Then asking for a simple physical requirement enables a transforming of the computed numbers to the actual tube.

Most of the features of the wave interaction problem in the straight shock tube are well known. The interactions delineate in the (x,t) - plane a number of regions of shock tube flow. These have been labeled in the Figure 5 according to standard practice. We focus on the interactions involving the reflected leading and trailing waves of the expansion fan connecting straight shock tube regions 4 and 3. Where and when these overtake the incident shock wave tell a) where a test wall should be placed to experience a peaked pressure pulse and b) what positive duration is to be expected. Conversely, if the positive duration is specified, the problem formulation allows driver and driven lengths to be determined.

Thus, considering the propagation of the forward-facing, reflected rarefaction waves R, we note that they will first interact at the contact surface K. This interaction may lead to weak reflected rarefaction or compression waves, but always to a transmitted rarefaction wave. The transmitted rarefaction wave thus continues onward, overtakes and interacts with the primary shock. This interaction gives rise to four possibilities depending on relative strengths of the

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5. *I. I. Glass and J. G. Hall, Handbook of Supersonic Aerodynamics, Section 18, Shock Tubes, NAVORD Report 1488 (Vol. 6) 1959.*

interacting waves: strong rarefaction wave relative to shock gives 1) reflected rarefaction or 2) compression waves and a transmitted rarefaction wave; or weak rarefaction wave relative to shock gives 3) reflected rarefaction or 4) compression waves and a transmitted (weakened) shock. The different initial conditions required to achieve these cases could be a means of achieving different pressure pulses with changed wave slopes, if desirable. For this study it turns out that the last-named interactions did not have to be considered in such detail.

B. Determination of Wave Speeds

The progress of the $R_{\rightarrow}$ wave* from the breech after reflection requires knowledge of its wave speed C through the various uniform regions. The wave speed is obtained from the Riemann invariants governing the simple flow. Across the backward facing $R_{\leftarrow}$ wave connecting regions 3 and 4:

$$\frac{2}{\gamma_4 - 1} a_4 = u_3 + \frac{2}{\gamma_4 - 1} a_3 = a_3 \left(M_3 + \frac{2}{\gamma_4 - 1}\right)$$

$$u_4 = 0$$

$$\frac{a_4}{a_3} = \frac{\gamma_4 - 1}{2} M_3 + 1 \quad ,$$

$$u_3 = \frac{2}{\gamma_4 - 1} (a_4 - a_3) \quad ,$$

$$\frac{p_4}{p_3} = \left(\frac{a_4}{a_3}\right)^{\frac{2\gamma_4}{\gamma_4 - 1}} \quad ;$$

Wave Speeds: $C_{-}3 = u_3 - a_3$, $C_{-}4 = -a_4$

Across the forward-facing $R_{\rightarrow}$ wave connecting 3 with 5:

**The notation is R = rarefaction, S = shock, and arrows indicate direction; and $C_{-}4$ = wave speed of backward-facing wave in region 4.*

$$u_5 - \frac{2}{\gamma_4 - 1} a_5 = u_3 - \frac{2}{\gamma_4 - 1} a_3 = a_3 \left(M_3 - \frac{2}{\gamma_4 - 1}\right)$$

$$a_5/a_3 = 1 - \frac{\gamma_4 - 1}{2} M_3$$

$$u_5 = 0$$

$$\frac{p_5}{p_3} = \left(\frac{a_5}{a_3}\right)^{\frac{2\gamma_4}{\gamma_4 - 1}}$$

Wave speeds: $C_+ 3 = u_3 + a_3$; $C_+ 5 = + a_5$

Farther along, the interaction $R_{\rightarrow} K \rightarrow \left\{ \begin{array}{c} \text{weak } R_{\leftarrow} KR_{\rightarrow} \\ \text{or} \\ \text{weak} \\ \text{compress. wave, } S_{\leftarrow} KR_{\rightarrow} \end{array} \right.$

If we assume the result $R_{\leftarrow} KR_{\rightarrow}$, our calculations lead to a contradiction in the pressures across the wave as well as in the slopes of leading and trailing wave. In this regard, the criteria and outcome for this interaction, as stated by Courant and Friedricks,[6] page 180, give an incorrect result here, whereas those by Glass and Hall,[5] page 95-6, and Landau and Lifshitz[7] (for acoustic waves) page 255-6, predict the results we indeed find.

The interaction results, then, in reflected compression waves coalescing to a shock and a transmitted rarefaction wave. For the weak waves expected here, the compression waves have the same properties as weak shocks.[5] Hence we assume the shock wave equations are applicable and also that entropy changes across the "forming shock" may be neglected, i.e., the process is also assumed to be isentropic.

With these assumptions, regions 5 and 6 are connected by

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6. *R. Courant and K. D. Friedrichs, Supersonic Flow and Shock Waves, Interscience Publishers, Inc., New York (1948).*

7. *L. D. Landau and E. M. Lifshitz, Fluid Mechanics, Pergamon Press Ltd., London, 1959.*

$$u_6 = u_5 - a_5 \left(\frac{p_6}{p_5} - 1\right) \sqrt{\frac{2/\gamma_4}{(\gamma_4+1)(p_6/p_5) + (\gamma_4-1)}}$$

and

$$\frac{p_6}{p_5} = \left(\frac{a_6}{a_5}\right)^{\frac{2\gamma_4}{\gamma_4-1}}$$

using the isentropic assumption.

On the other side of the contact surface, across the transmitted forward-facing $R_{\rightarrow}$ connecting regions 2 and 7, one has

$$u_2 - \frac{2}{\gamma_1-1} a_2 = u_7 - \frac{2}{\gamma_1-1} a_7$$

and

$$\frac{p_7}{p_2} = \left(\frac{a_7}{a_2}\right)^{\frac{2\gamma_1}{\gamma_1-1}}$$

where the known conditions for region 2 are obtained from the shock strength p_2/p_1 or M_s, i.e., from tables of straight shock tube properties.

The first equation is recast into more useful form:

$$u_7 = u_2 + \frac{2}{\gamma_1-1} a_2 \left[\left(\frac{p_7}{p_2}\right)^{\frac{\gamma_1-1}{2\gamma_1}} -1\right] ,$$

and making use of equalities across the contact surface

$$u_6 = u_7, \; p_6 = p_7; \; p_3 = p_2$$

results in

$$u_7 = u_2 + \frac{2}{\gamma_1 - 1} a_2 \left[\left(\frac{p_7}{p_5} \cdot \frac{p_5}{p_3} \right)^{\frac{\gamma_1 - 1}{2\gamma_1}} - 1 \right] = u_6$$

$$= u_5 - a_5 \left(\frac{p_7}{p_5} - 1 \right) \sqrt{\frac{2/\gamma_4}{(\gamma_4+1)(p_7/p_5) + (\gamma_4 - 1)}} ,$$

yielding a single equation for p_7/p_5 in terms of previously determined quantities. Solution then permits the calculation of particle and sound speeds u_6, a_6 and u_7, a_7 applicable for these regions.

The transmitted leading and trailing waves of the expansion then propagate onward with velocities (u_2+a_2) and (u_7+a_7), respectively, to interact with the shock giving the locations within which one may expect a peaked wave, and also determining its duration. Specific cases of test conditions must now be entered to obtain actual numbers. The problem formulation is usually done in non-dimensional coordinates

$X = \frac{x}{L}$, $\tau = \frac{at}{L}$ where L and a are convenient reference length and sound speed, respectively. The non-dimensional time interval between intersection of leading and trailing waves of the expansion with the shock thus yields the reference length, if we set the real time interval equal to the pulse duration. The numbers as yet apply to a straight shock tube, chosen to give the desired equivalent downstream conditions.

In converting over to the area-changed shock tube, we recognize that the driver lengths should not in general be equal, since different pressure ratios are involved across the diaphragm. Thus, velocities and wave speeds must be different; and, the wave speed in the area-changed tube must slow down in the steady, subsonic expansion to match the downstream conditions set for the equivalent straight shock tube.

The wave diagram in Figure 6 shows a possible wave-speed comparison (as seen from numbers to be given later) and illustrates how a simple conversion of tube lengths may be made: we demand that the real times be equal, for both straight and area-changed shock tubes, for the leading wave of expansion to be reflected from breech and to travel back to the diaphragm station. The flows to the leading waves are then identical beyond, neglecting the time required in traversing the short transition piece (which implies an assumption on the length of this piece).

This particular calculation may be done analytically for the intersection point of leading with trailing wave of the reflected expansion[8] and wave progress then continued at constant speed to the diaphragm station X = 0 at τ_o.

From the nondimensional times

$$\Delta\tau = \frac{a_4 \Delta t}{L_4}$$

the real times for the arrival at X = 0 are equated

$$\Delta t = \left.\frac{L_4\ \Delta\tau}{a_4}\right)_{str} = \left.\frac{L_4\ \Delta\tau}{a_4}\right)_c$$

to arrive at driver length conversion.

C. Sample Calculated Wave Speeds and Results

The actual test conditions are used in the calculations outlined. As a specific example, we choose the test condition p_{2g} = 73 kPa (10.6 psi). For this case the previously obtained flow parameters are given to an equivalent straight shock tube:

$M_1 = 1.27$ $\qquad\qquad$ $\gamma_1 = \gamma_4 = 7/5$

$p_2/p_1 = 1.72$

$u_2 = 0.4022a_1 = u_3$

$M_3 = u_3/a_3 \doteq 0.5$ $\quad$ ($M_{3a} = 0.6$ for $A_4/A_1 = 0.444$)

$a_3 = 0.8044a_1$

With these conditions, the driver sound speed is

$a_4 = 0.88484a_1$

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8. *R. K. Lobb, "On the Length of a Shock Tube," UTIA Report 5, Institute of Aerophysics, University of Toronto, 1950.*

Then the wave speeds for the reflected expansion are

$$C_+3 \equiv u_3 + a_3 = (0.4022 + 0.8044)a_1 = 1.2066a_1$$

$$C_+5 \equiv u_5 + a_5 = 0.72396\ a_1$$

$$C_+2 \equiv u_2 + a_2 = (0.4022 + 1.083)a_1 = 1.4852a_1$$

$$C_+7 \equiv u_7 + a_7 = (-0.0610 + 0.9911)a_1 = 0.9301\ a_1$$

$$(C_-4 \equiv u_4 - a_4 = -\ 0.88484\ a_1)$$

$$(C_-3 \equiv u_3 - a_3 = -\ 0.4022a_1)$$

With these results, one is in position to follow the rarefaction wave from diaphragm break to its interaction with the primary shock.

A characteristics calculation with desk calculator yields the extent of the breech reflection, for leading (ℓ) and trailing (t) waves:

$$X = -\ 1.0, \quad \begin{matrix} \tau_\ell = 1.1301 \\ \tau_t = 2.15147 \end{matrix} \qquad (\tau \equiv \frac{a_1\ t}{L_4}\ \text{here})\ .$$

The intersection point X_3 of reflected leading wave with trailing wave is found to be

$$X_3 = -\ 0.6094;\ \tau_3 = 1.5151.$$

Continuing, the reflected leading and trailing waves moving with velocities C_+3 and C_+5, respectively, overtake the contact surface K moving with velocity u_2. We have bypassed a detailed (but more accurate) characteristics calculation, and have followed both waves' arrival only up to the leading wave's intersection with K, at X_K:

$$X_K = 1.21876, \quad \begin{matrix} \tau_{K,\ell} = 3.0302 \\ \tau_{K,t} = 5.21607 \end{matrix}$$

This procedure, as seen by inspection of the wave diagram, Figure 5,

should give a lower estimate on the actual trailing wave's intersection point with K and hence an upper estimate to be made on the tube lengths.

Beyond the contact surface K, the transmitted leading and trailing waves of the rarefaction move to intersection with the shock, with velocities C_+2 and C_+7, respectively. The procedure for this interaction is again to follow the rarefaction waves only up to the leading wave's intersection X_s with shock. Here also a detailed characteristics calculation is bypassed in the interest of simplicity. Similarly, a lower estimate on actual intersection position and time is expected for the trailing wave. The results then are

$$\tau_{s,\ell} = 15.2495$$

$$X_s = 19.367, \qquad \tau_{s,t} = 24.728$$

The (nondimensional) interaction time

$$\Delta\tau = \tau_{s,t} - \tau_{s,\ell} \equiv \frac{a_1 \Delta t}{L_4}$$

thus fixes the desired peaked wave's duration (which may be transmitted with some positive pressure, depending on conditions, nevertheless). Choosing the wave duration $\Delta t = 50$ ms then determines the required (straight tube) driver length:

$$L_{4\ str} = \frac{a_1\ 50\ (10^{-3})}{\Delta\tau}$$

$$L_{4\ str} = 1.77\text{m (5.80 ft.)} \quad (a_1 = 335 \text{ m/s or } 1100 \text{ ft/s})$$

The test wall is placed at X_s, where the leading wave of the rarefaction intersects the primary shock and determines the driven tube length L_1:

$$L_1 = X_s\ L_4 = 19.367\ (1.77\text{m})$$

$$L_1 = 34.3\text{m (112.3 ft)};$$

as we have remarked earlier, L_1 as determined is probably an upper estimate.

These numbers are as yet based on the straight shock tube with downstream conditions identical to the desired conditions. To maintain this identity through wave speeds and interaction points in the wave diagram, we asked that the real times be equal after diaphragm break - for straight and for area-changed tube - for the leading waves of the expansions to travel back to the diaphragm station. Thus, using the numbers appropriate for the straight tube and for the area-changed tube for the case considered in the beginning of this section and following the procedure outlined earlier, we arrive at

$$\Delta t = L_{4c} \frac{\Delta\tau_c}{a_{4c}} = L_{4\ str} \frac{\Delta\tau_{str}}{a_{4\ str}}$$

and with numbers inserted

$$\Delta t = L_{4c} \frac{1.756}{a_1} = L_{4\ str} \frac{1.7747}{0.88484\ a_1}$$

or

$$L_{4c} = 1.142\ L_{4\ str}$$

For $L_{4\ str}$ = 1.77m (5.80 ft),

$$L_{4c} = 2.02\text{m } (6.62 \text{ ft})$$

Then, having forced this partial simultaneity on driver wave motions, we are assured that the downstream behavior in the two shock tubes will be reasonably matched. Hence the driven tube length is as computed- 34.3m (112 ft).

IV. CONCLUSIONS

Using an extension of the normal straight shock tube operating cycle, we have determined appropriate tube lengths and driver pressures for requisite operation/modification of an existing BRL 2.4m (8') shock tube to permit full scale testing. Walls and structures of 3.7m (12') height are acceptable for simulated blast loadings of ~70 kPa (10 psi) having pulse durations of 50 ms. Other loadings and the appropriate tube lengths are derivable without difficulty using the procedures developed.

The results are based on idealized shock tube operation, with approximations introduced to obviate the need for an extensive computer program. In an actual design to the full sized tube, one

should expect departures from such ideal operation due to boundary layer growth and imperfect diaphragm effects such as non-instantaneous opening and loss of energy to the opening process.

Due to the relatively short length of driver required, a much smaller prototype tube with required area change ratio could be constructed from BRL existing shock tubes, and the wave characteristics determined empirically and compared with calculations, to see what modifications should be incorporated into the full sized facility.

ACKNOWLEDGMENT

The author thanks Dr. K. S. Fansler for helpful discussion and clarification of ideas.

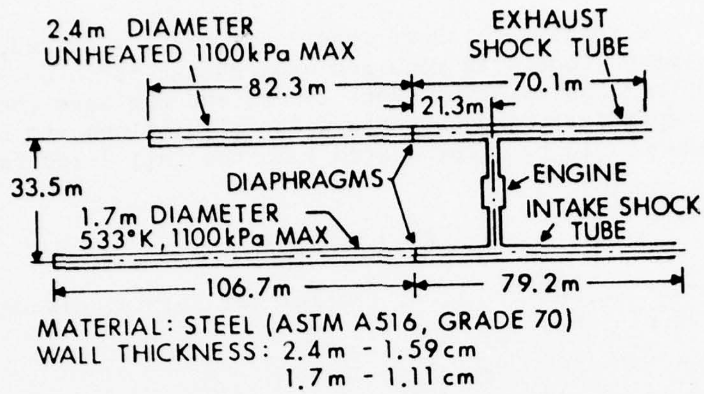

Figure 1. BRL Dual Shock Tube Facility

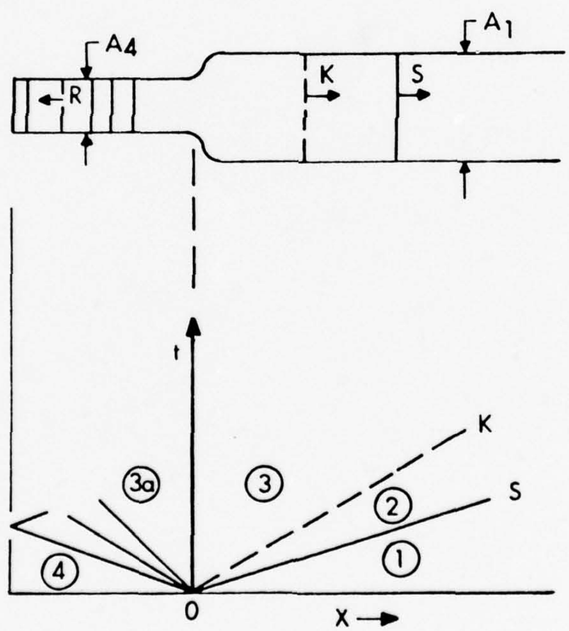

Figure 2. Wave Diagram of Idealized Shock Tube with Area Change at Diaphragm

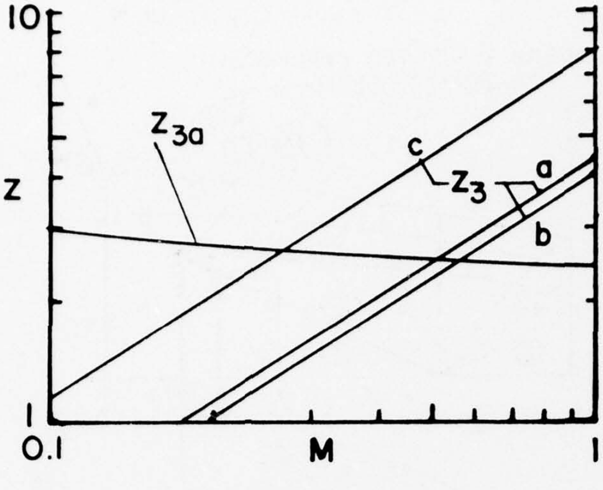

Figure 3. Graphical Solution to Equation (8): Curves Z_{3a} and Z_3 as a Function of Mach Number

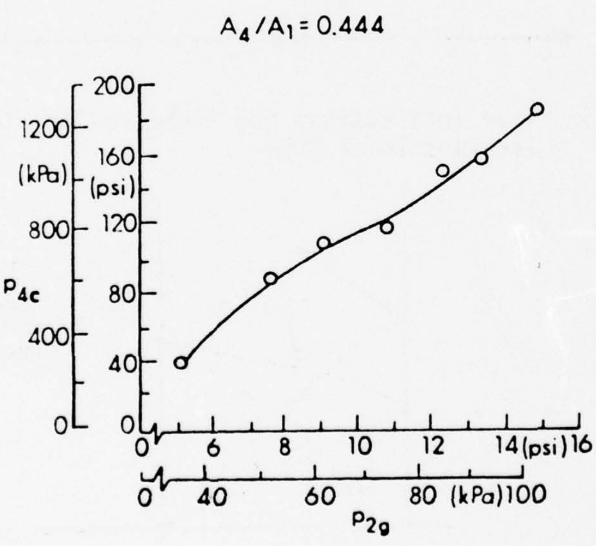

Figure 4. Driver Pressure - Testing Pressure for 2.4m: 3.7m (8':12') Area Changed Shock Tube

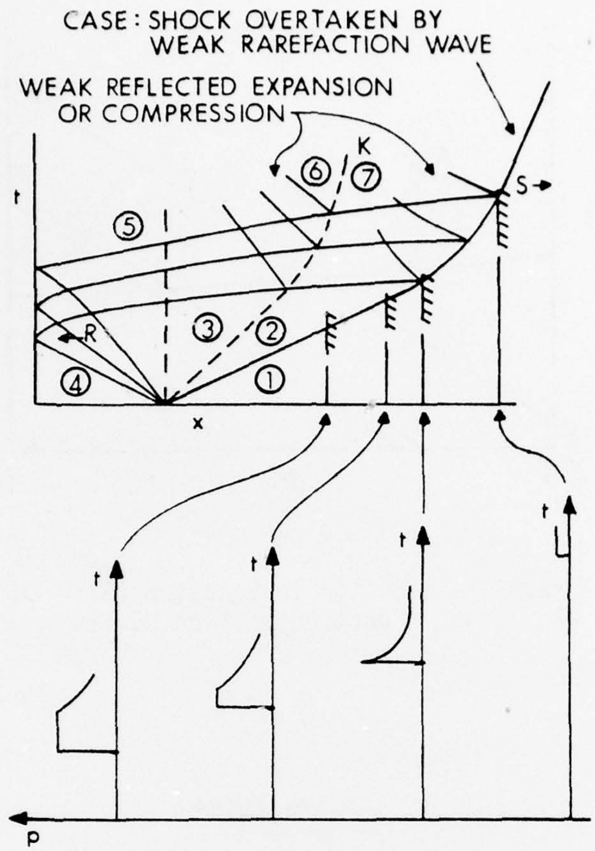

Figure 5. Wave Interactions and Pressures at Stations x: Straight Shock Tube

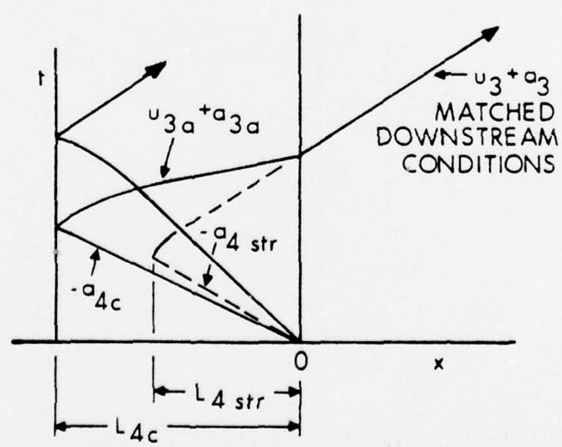

Figure 6. Wave Diagram Illustrating Driver Tube Lengths Relationship

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